

# The strongest bounds on active-sterile neutrino mixing after Planck data\*

Alessandro Mirizzi,<sup>1</sup> Gianpiero Mangano,<sup>2</sup> Ninetta Saviano,<sup>1,2,3</sup> Enrico  
 Borriello,<sup>1</sup> Carlo Giunti,<sup>4</sup> Gennaro Miele,<sup>2,3</sup> and Ofelia Pisanti<sup>2,3</sup>

<sup>1</sup>*II Institut für Theoretische Physik, Universität Hamburg,  
 Luruper Chaussee 149, 22761 Hamburg, Germany*

<sup>2</sup>*Istituto Nazionale di Fisica Nucleare - Sezione di Napoli,  
 Complesso Universitario di Monte S. Angelo, I-80126 Napoli, Italy*

<sup>3</sup>*Dipartimento di Fisica, Università di Napoli Federico II,  
 Complesso Universitario di Monte S. Angelo, I-80126 Napoli, Italy*

<sup>4</sup>*Department of Physics, University of Torino and INFN, Via P. Giuria 1, I-10125 Torino, Italy*

Light sterile neutrinos can be excited by oscillations with active neutrinos in the early universe and contribute as extra-radiation, parameterized in terms of the effective number of neutrino species  $N_{\text{eff}}$ . This parameter has been measured to quite a good precision by the Planck satellite experiment, yielding  $N_{\text{eff}} = 3.30 \pm 0.27$  at 68 % C.L. We use this result to update the bounds on the parameter space of (3+1) sterile neutrino scenarios, with an active-sterile neutrino mass squared splitting in the range  $(10^{-5} - 10^2) \text{ eV}^2$ , in both normal and inverted mass hierarchies for the active and sterile states. For the first time we take into account the possibility of two non-vanishing active-sterile mixing angles. We find that the bounds are stronger than those obtained in laboratory experiments. In fact, we get active-sterile mixing angles  $\sin^2 \theta_{i4} \lesssim 10^{-2.5}$  for mass splittings  $\Delta m_{41}^2 > 10^{-1} \text{ eV}^2$ . This result leads to a strong tension with the short-baseline hints of light sterile neutrinos. In order to relieve this disagreement, modifications of the standard cosmological scenario, e.g. large primordial neutrino asymmetries, are required.

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*Introduction.*— Light sterile neutrinos have been advocated as a possible solution to some puzzling results found in neutrino oscillations, see [1] for a recent review. In particular,  $m \sim \mathcal{O}(1) \text{ eV}$  sterile neutrinos mixing with the active states have been proposed to solve different anomalies observed in short-baseline neutrino experiments, in the  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  oscillations in LSND [2] and Mini-Boone [3, 4] experiments, and in  $\bar{\nu}_e$  and  $\nu_e$  disappearance revealed by the Reactor Anomaly [5] and the Gallium Anomaly [6], respectively. Scenarios with one (dubbed “3+1”) or two (“3+2”) sub-eV sterile neutrinos [7, 8] have been proposed to fit the different data. On the other hand, lighter sterile neutrinos with  $\Delta m^2 \sim 10^{-5} \text{ eV}^2$  can explain the absence of the upturn in the solar neutrino energy spectrum [9].

The main theoretical motivations for these states are perhaps not so strong, though light sterile neutrinos with a sizable mixing emerge in several models (see, e.g., [10] and references therein). In any case, their role as messengers of new physics is relevant enough to justify an open mind attitude and a close looking for any, yet tiny, evidence for new effects beyond the *too much* successful Standard Model.

The hunt for sterile neutrinos in laboratory experiments is currently open. Different techniques have been proposed to search for these elusive particles (see, e.g., [11]). Indeed, since every experimental measure-

ment has its own systematic uncertainties and its own recognized or un-recognized loop holes, in order to corner the sterile neutrino parameter space it is worth using as many handles as possible (see, e.g., [12]). Cosmology is one of the most powerful tool (see, e.g., [13]). Adding exotic contribution to the radiation content in the universe, usually expressed in terms of the effective number of excited neutrino species,  $N_{\text{eff}}$ , has in fact, a big impact on both the Cosmic Microwave Background (CMB) anisotropy map [14–17], and the Big Bang Nucleosynthesis (BBN) nuclear species yields [18, 19]. The standard expectation for this parameter is  $N_{\text{eff}} = 3.046$  [20]. If low-mass sterile neutrinos exist and mix with active flavors, they can be thermally excited by the interplay of oscillations and collisions, producing a larger value of  $N_{\text{eff}}$ . Cosmological constraints on sterile neutrinos based on their contribution to the extra-radiation have been presented in several papers, see e.g. [13, 21–23].

In the last few years, a possible cosmological hint of light sterile neutrinos (see e.g. [24, 25]) was found by combining the result in the best fit of WMAP, SDSS II-Baryon Acoustic Oscillations and Hubble Space Telescope data, yielding a 68 % C.L. range on  $N_{\text{eff}} = 4.34^{+0.86}_{-0.88}$  [14] for a  $\Lambda$ CDM universe. The recent results of WMAP-9 [15], SPT [16] and ACT [17], exploiting the damping tail features at high multipoles, have weakened this evidence to less than  $2\text{-}\sigma$ .

A recent breakthrough in constraining the *dark* radiation content in the early universe is represented by the first data release of the Planck collaboration [26], a satellite experiment with unprecedented sensitivity in the high multipole range. Indeed, one of the main result

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of this new CMB anisotropy map is the quite accurate estimate of the relativistic degrees of freedom at recombination epoch,  $N_{\text{eff}} = 3.30 \pm 0.27$  at 68 % C.L., a result obtained combining Planck, WMAP, Baryon Acoustic Oscillation and high multipole CMB data [26]. Within  $1\text{-}\sigma$  this is compatible with the standard expectation, but still leaves room for almost an extra neutrino species at 95 % C.L.

This result is the motivation of this paper, where we present an update of the cosmological bounds on light sterile neutrinos. We focus on (3+1) scenarios, considering a broad range for active-sterile neutrino mass splitting, which cover the regions where laboratory hints emerge. We have chosen to consider a minimal scenario (one extra sterile state only), and not to cover the (3+2) case, where it seems harder to fit the neutrino mass bound from large scale structure [24]. This case also appears to be disfavored by Planck results unless one considers large neutrino asymmetries to suppress the sterile neutrino production, see e.g. [22, 27].

*Setup of the (3+1) flavor evolution.*— We consider one single light sterile neutrino  $\nu_s$ , which mixes with the active neutrino states  $\nu_e, \nu_\mu, \nu_\tau$ . The flavor eigenstates  $\nu_\alpha$  are related to the mass eigenstates  $\nu_i$  via a unitary matrix  $\mathcal{U} = \mathcal{U}(\theta_{12}, \theta_{13}, \theta_{23}, \theta_{14}, \theta_{24}, \theta_{34})$  [1, 28] where we order the flavor eigenstates in such a way that if all mixing angles are vanishing we have  $(\nu_e, \nu_\mu, \nu_\tau, \nu_s) = (\nu_1, \nu_2, \nu_3, \nu_4)$ . In the following we fix the values of the three active mixing angles to the current best-fit from global analysis of the different active neutrino oscillation data [29],  $\sin^2 \theta_{12} = 0.307$ ,  $\sin^2 \theta_{23} = 0.398$ , and  $\sin^2 \theta_{13} = 0.0245$ . Concerning the mixing angles between active and sterile neutrinos we choose as representative range  $10^{-5} \leq \sin^2 \theta_{i4} \leq 10^{-1}$  ( $i=1,2,3$ ).

The  $4\nu$  mass spectrum is parameterized as  $\mathcal{M}^2 = \text{diag}(m_1^2, m_1^2 + \Delta m_{21}^2, m_1^2 + \Delta m_{31}^2, m_1^2 + \Delta m_{41}^2)$ . The solar and the atmospheric mass-square differences are given by  $\Delta m_{21}^2 = m_2^2 - m_1^2 = 7.54 \times 10^{-5} \text{ eV}^2$  and  $|\Delta m_{31}^2| = |m_3^2 - m_1^2| = 2.43 \times 10^{-3} \text{ eV}^2$ , respectively [29]. Depending on the sign of  $\Delta m_{31}^2$  and  $\Delta m_{41}^2$  we define an active normal mass hierarchy (NH,  $m_3 > m_1$ ) or an active inverted mass hierarchy (IH,  $m_3 < m_1$ ) and a sterile normal mass hierarchy (SNH,  $m_4 > m_1$ ) or a sterile inverted mass hierarchy (SIH,  $m_4 < m_1$ ). In our study we consider the following ranges  $10^{-5} \leq \Delta m_{41}^2 / \text{eV}^2 \leq 10^2$  in SNH and  $10^{-5} \leq |\Delta m_{41}^2| / \text{eV}^2 \leq 10^{-2}$  in SIH. Note that in SIH larger values of  $|\Delta m_{41}^2|$  are disfavored due to the cosmological bounds on the neutrino masses [15, 26].

The neutrino (antineutrino) ensemble in a medium, as in the early universe plasma, is described in terms of a  $4 \times 4$  momentum-dependent density matrix  $\varrho_{\mathbf{p}}(\bar{\varrho}_{\mathbf{p}})$ . To solve the full set of momentum dependent equations of motion [30] turns out to be a computationally demanding task (see, e.g., [23, 27] for recent studies). Since our aim is to perform an extensive scan of the sterile neutrino parameter space, in order to carry out a more treatable numerical analysis, we will consider the averaged-momentum approximation, based on

the ansatz,  $\varrho_{\mathbf{p}}(T) \rightarrow f_{FD}(p) \rho(T)$  (see [31]) where  $\rho(T)$  is the density matrix for the mean thermal momentum  $\langle p \rangle = 3.15 T$ , and  $f_{FD}(p)$  is the Fermi-Dirac neutrino equilibrium distribution, and similarly for antineutrinos.

The evolution equation for the momentum-averaged density matrix  $\rho$ , describing the neutrino system, is the following [30, 31]:

$$i \frac{d\rho}{dt} = [\Omega, \rho] + C[\rho, \bar{\rho}], \quad (1)$$

and a similar expression holds for the antineutrino matrix  $\bar{\rho}$ . The evolution in terms of the comoving observer proper time  $t$  can be easily recast in function of the temperature  $T$  (see [31] for a detailed treatment). The first term on the right-hand side of Eq. (1) describes the flavor oscillations Hamiltonian,

$$\Omega = \frac{M^2}{2} \left\langle \frac{1}{p} \right\rangle + \sqrt{2} G_F \left[ -\frac{8p}{3m_w^2} (\mathbf{E}_\ell + \mathbf{E}_\nu) + \mathbf{N}_\nu \right], \quad (2)$$

where  $M^2 = \mathcal{U}^\dagger \mathcal{M}^2 \mathcal{U}$  is the neutrino mass matrix, while the terms proportional to the Fermi constant  $G_F$  encode the matter effects in the neutrino oscillations. In particular, the term  $\mathbf{E}_\ell$  is related to the energy density of  $e^\pm$  pairs,  $\mathbf{E}_\nu$  to the energy density of  $\nu$  and  $\bar{\nu}$ , and  $\mathbf{N}_\nu$  is the  $\nu - \nu$  interaction term proportional to the neutrino asymmetry. In the following, we will consider the most conservative scenario, with zero neutrino asymmetries, or as small as the baryon asymmetry,  $\eta_B \sim 6 \cdot 10^{-10}$ . Finally, the last term in the right-hand side of Eq. (1) is the order  $G_F^2$  collisional term.

The matter terms can induce Mikheyev-Smirnov-Wolfenstein (MSW)-like resonances [32] between the active and sterile states when they become  $\mathcal{O}(\Delta m_{4i}^2)$ . The possible resonances depend on the different mass hierarchies in the active and sterile neutrino sector. In particular, in the absence of neutrino asymmetries the resonance condition can be satisfied (in both neutrino and antineutrino sectors) only for  $\Delta m_{4i}^2 < 0$  [31]. When more than one  $\Delta m_{4i}^2$  is negative, multiple resonance can occur, affecting the sterile neutrino production.

*Bounds on active-sterile  $\nu$  mixing after Planck.*— The quantity we are exploiting to constrain the sterile neutrino parameter space is the overall non electromagnetic radiation content, parametrized via  $N_{\text{eff}}$ ,

$$N_{\text{eff}} = \frac{1}{2} \text{Tr}(\rho + \bar{\rho}) . \quad (3)$$

Our bounds are given comparing this number with the one measured by Planck experiment,  $N_{\text{eff}} < 3.84$  at 95 % C.L. [26]. We present our exclusion plots in the planes  $(\Delta m_{41}^2, \sin^2 \theta_{i4})$ . We checked that our results are not sensitive to the active neutrino mass ordering. Therefore, in the following we show our findings only for NH, while we consider both SNH and SIH. Since the results as a function of  $\sin^2 \theta_{34}$  and  $\sin^2 \theta_{24}$  are very similar, we omit to present the  $\sin^2 \theta_{34}$  case. In Figure 1 we show the exclusion plots at 95 % C.L. In the upper panels a), b)

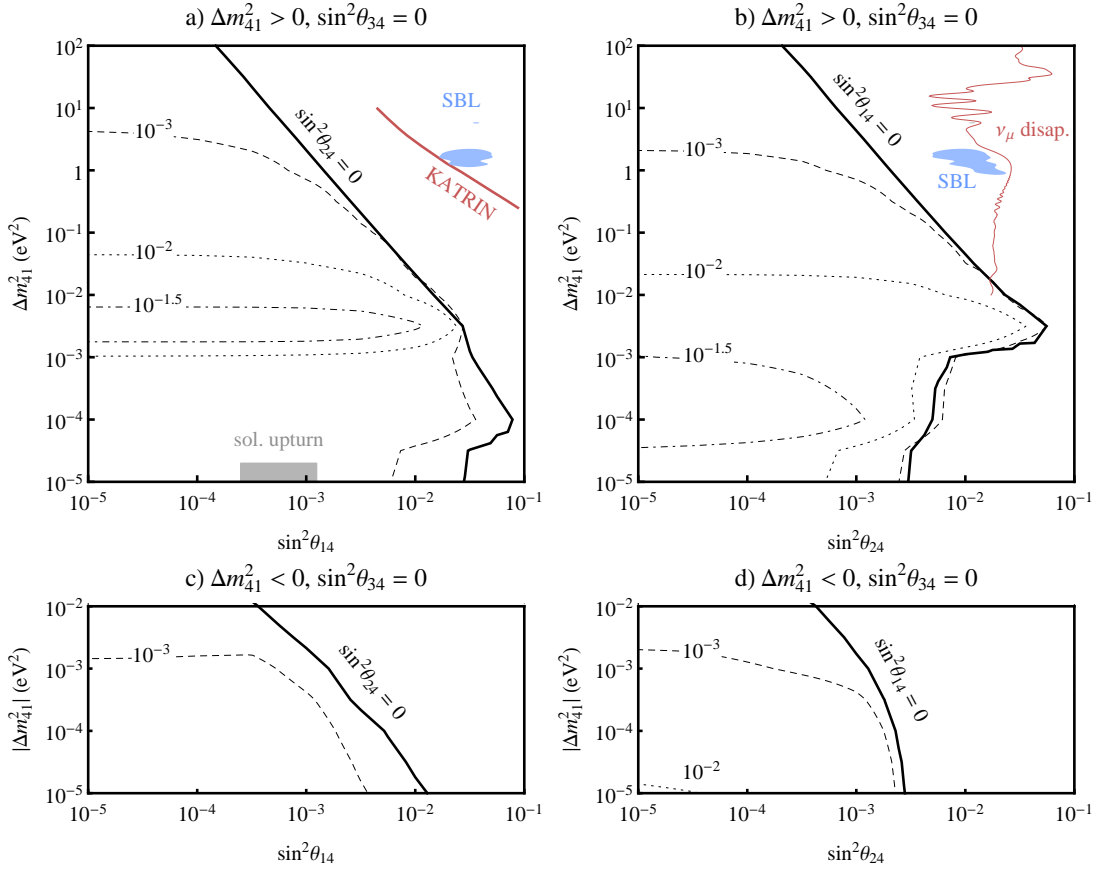


FIG. 1: Exclusion plots for the active-sterile neutrino mixing parameter space for different scenarios (see the text for details).

we consider SNH, while in the lower panels c), d) we show the SIH case. Left panels refer to the exclusion plots in the plane  $(\Delta m_{41}^2, \sin^2 \theta_{14})$  for different values of  $\sin^2 \theta_{24}$ , while right panels refer to the plane  $(\Delta m_{41}^2, \sin^2 \theta_{24})$  for different values of  $\sin^2 \theta_{14}$ . In all the cases,  $\sin^2 \theta_{34}$  is fixed to zero. The excluded regions are those on the right or at the exterior of the (closed) contours. We now discuss the different panels in more details.

*Panel a)* The most conservative bound corresponds to  $\sin^2 \theta_{24} = 0$ , where for  $\Delta m_{41}^2 \gtrsim 10^{-2} \text{ eV}^2$  the exclusion contour is a straight line in this plane. Lowering the value of  $\Delta m_{41}^2$  one triggers first a  $\nu_4 - \nu_3$  resonance (when  $\Delta m_{41}^2 < \Delta m_{31}^2$ ) and then also a  $\nu_4 - \nu_2$  resonance (when  $\Delta m_{41}^2 < \Delta m_{21}^2$ ) which is the dominant one. These produce the changes of the slope in the exclusion plot. In particular, increasing the value of  $\sin^2 \theta_{24}$ , the constraint on the parameter space becomes stronger. Large values of  $\sin^2 \theta_{24}$  would dominate the sterile neutrino production and this excludes regions otherwise permitted if only  $\sin^2 \theta_{14}$  were non-zero. In particular, the only part that remains open is the transition region between the efficient non-resonant production range at large  $\Delta m_{41}^2$  and the one of resonant production at small  $\Delta m_{41}^2$ . For comparison, we also show the slice at  $\sin^2 \theta_{24} = 10^{-2}$  of the 95 % C.L., allowed region obtained from the global anal-

ysis of short-baseline oscillation data [7, 33] (filled region in the up right part of the plot denoted by SBL). We see that it seems to be completely ruled out by the cosmological bound. We also plot the 90 % C.L. expected sensitivity of the KATRIN experiment (measuring the spectrum of electrons from tritium beta decay) after 3-years of data taking [34]. Also this region would be already excluded by cosmology in absence of any significant primordial neutrino asymmetry [22, 23, 27, 31]. Finally, we represent with a square in the lower part of the plot, the region of parameters corresponding to a light sterile neutrino with  $\Delta m_{41}^2 \simeq 10^{-5} \text{ eV}^2$  and  $\sin^2 \theta_{14} \sim 10^{-4} - 10^{-3}$ , suggested to solve the problem of the upturn of the solar neutrino spectrum [9].

*Panel b)* The description of the exclusion plot is analogous to the one of panel a), with the roles of  $\theta_{14}$  and  $\theta_{24}$  interchanged. In particular, the region of resonant sterile neutrino production is at  $\Delta m_{41}^2 \simeq 10^{-3} \text{ eV}^2$  when a  $\nu_4 - \nu_3$  resonance is efficient. We have also drawn the slice at  $\sin^2 \theta_{14} = 10^{-1.5}$  of the 95 % C.L. allowed region obtained from the global analysis of short-baseline oscillation data [7, 33], which is another view of the SBL region shown in panel a), and the exclusion curve obtained from the combined analysis of the data of  $\nu_\mu$  and  $\bar{\nu}_\mu$  disappearance experiments. One realizes that also in

this case the region is excluded by the cosmological limit.

*Panels c) and d)* Since  $\Delta m_{41}^2 < 0$  also a  $\nu_4$ - $\nu_1$  resonance is present. This leads to an increase in the production of sterile neutrinos, with respect to the case of SNH. Therefore, the excluded regions in the parameter space are larger than the corresponding ones in the upper panels.

*Conclusions.*— In this paper we have exploited the very recent measurement of  $N_{\text{eff}}$  provided by the Planck experiment to update the cosmological bounds on (3+1) sterile neutrino scenarios under the assumption of vanishing or very small neutrino asymmetries, of the order of the baryonic one. To our knowledge, for the first time it is shown how the constraints change if two active-sterile mixing angles are considered.

We find that the sterile neutrino parameter space seems now to be severely constrained, and the excluded area covers the region accessible by current and future laboratory experiments. From the results of our analysis we conclude that there is a tension with the sterile neutrino hints from short-baseline experiments. Notice that combining Planck findings with other data might further strengthen the bounds on  $N_{\text{eff}}$ . For example, adding in the analysis the primordial deuterium determination of Ref. [35], compared with the BBN theoretical expectation as function of baryon density and  $N_{\text{eff}}$ , leads to  $N_{\text{eff}} \leq 3.56$  at 95 % C.L. [26]. This means that future

$^2\text{H}$  measurements reducing the present spread of different Quasar Absorption System results would lead to stronger bounds on sterile neutrino mixing parameters.

In order to reconcile the laboratory signals in favor of extra sterile neutrino degrees of freedom with the cosmological bounds one should introduce some extra parameters in the so far extremely successful standard cosmological model, as for example, large neutrino-antineutrino asymmetries,  $L_\nu = (n_\nu - n_{\bar{\nu}})/n_\gamma \gtrsim 10^{-2}$  [27, 31], which might inhibit the sterile neutrino production in the early universe. After all, the fact that a completely satisfactory model of everything might not yet achieved is welcome, as it would continue to trigger the curiosity of physicists to look for what is, hopefully, beyond the corner.

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